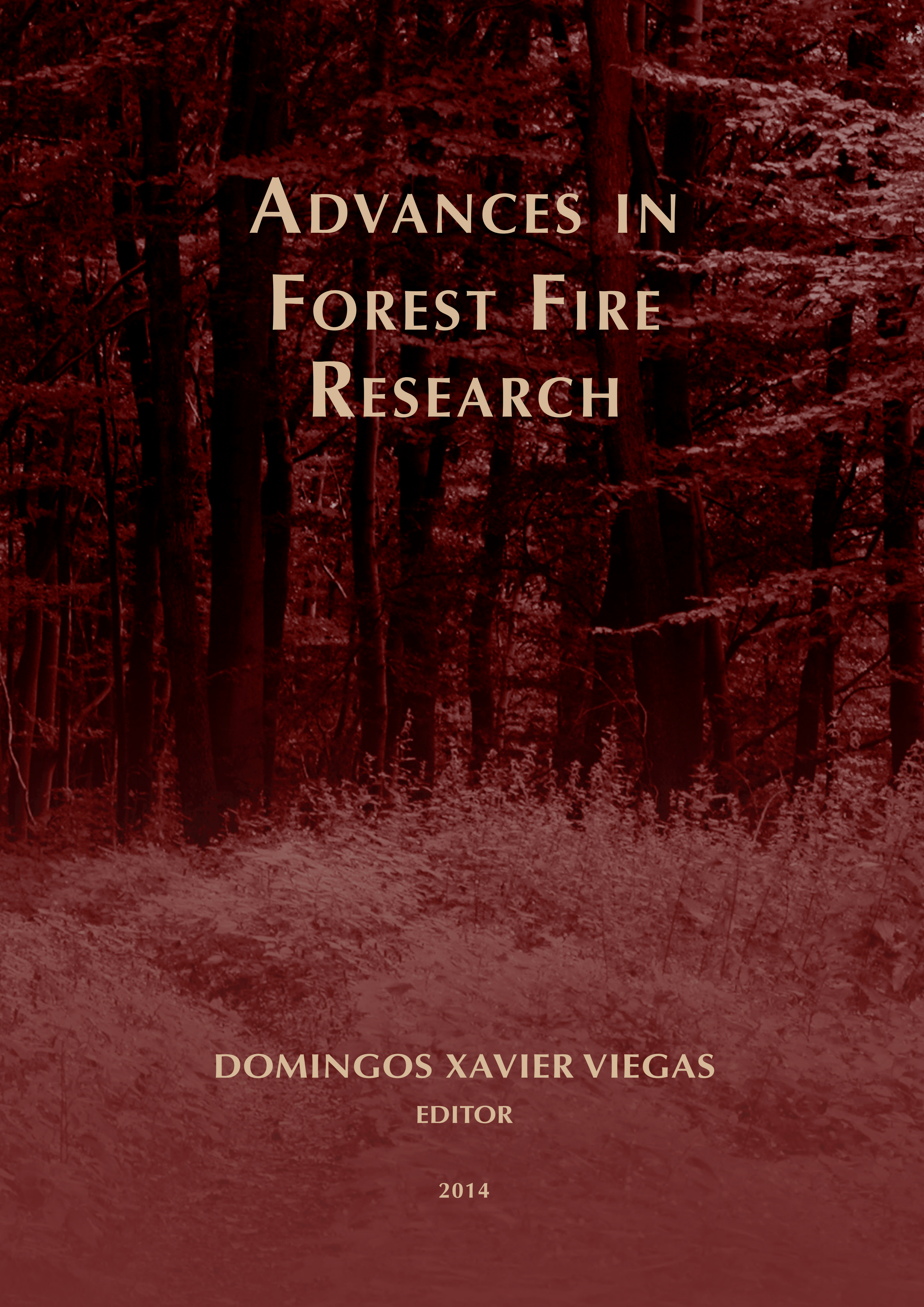

# Advances in Forest Fire Research

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# Wildfires in Mediterranean shrubs and grasslands, in Greece: In situ fire behaviour observations versus predictions

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**Abstract**

This paper presents a testing of surface wildfire rate of spread (ROS) field observations ($ROS_{observed(surface)}$) versus rate of spread predictions ($ROS_{predicted(surface)}$) from BehavePlus (Andrews *et al*., 2005) for tall and short Mediterranean shrublands, Sarcopoterium spinosum (small xeric shrub, up to 0.5 m height) and grass. In order to evaluate the degree of their agreement and analyse the results of their correlations, surface or passive crown fire behaviour data as well as meteorological, topography and forest fuels data had to be prepared according to specific criteria in order to ensure their quality and compatibility.

Ninety five fire behaviour data records were created from field observations and measurements made during the evolution of specific wildfires in Greece, in the last seven fire seasons (2007-2013). The data were classified depending on the fuel model that describes the fuel types they had spread in and, thus, four data subsets were generated that correspond to the following four fuel models for Greece which had been developed in 2001 (Dimitrakopoulos *et al* 2001, Dimitrakopoulos 2002): a) "Evergreen-schlerophyllous shrublands (1.5 - 3 m)" for tall maquis (38 cases), b) "Evergreen schlerophyllous shrublands (up to 1.5 m)" for short maquis (13 cases), c) "Phrygana II (Sarcopoterium spinosum)" for phryganic areas where the dominant species was Sarcopoterium spinosum (26 cases) and d) "Mediterranean grasslands" for grass (18 cases). After creating the database, the BehavePlus system was used to produce rate of spread predictions for each of the ninety five cases and flame length (FL) predictions ($FL_{predicted}$ values) for the twenty six cases of *Sarcopoterium spinosum* dominated phrygana fields.

The main finding is that for the four Greek fuel models tested, BehavePlus can be a useful tool for predictions of fire behaviour. However, there is a relatively consistent over-prediction of ROS for the models "Evergreen-schlerophyllous shrublands (1.5 - 3 m)" for tall maquis, "Evergreen schlerophyllous shrublands (up to 1.5 m)" for short maquis (13 cases), and "Phrygana II (Sarcopoterium spinosum)", while there a significant under-prediction for the "Mediterranean grasslands" fuel model.

Four linear regression equations describing mathematically the relation of the predicted to the observed ROS were developed. They are statistically significant and can be used for adjusting BehavePlus predictions to match "real world" fire behaviour.

A further finding was that flame length is seriously under-predicted when using BehavePlus with the Phrygana II fuel model to predict fire behaviour in *Sarcopoterium spinosum* dominated phrygana fields. This is an important result that can be very useful for the safety of firefighters.

***Keywords****: Mediterranean shrubs, maquis, phrygana, fuel model, wildfire behaviour prediction, BehavePlus, wildfire field observations, Greece*

## 1. Introduction

Modern wildfire management requires use of reliable fire behaviour prediction and fire spread simulation systems. However, broad operational adoption of such systems can be achieved and benefits can be maximized only if their strengths and generalizations, weaknesses or limitations are well known. Continuous and extensive testing of fire behaviour prediction systems in the laboratory, in experimental field burns as well as in actual wildfires, is necessary since it detects their "limits", documents their proper use and increases, eventually, their contribution to fire fighting safety and efficiency. Globally, fire managers and scientists often utilise data sets that come from documented wildfires and test the predictions of fire behaviour modelling systems, such as the popular system BehavePlus (Andrews *et al*., 2005), versus field observations, aiming to evaluate the degree of their agreement. Measurements of weather conditions and topography as well as information about the forest fuels (fuel models), are necessary as inputs for using the BehavePlus system. Until now, many studies have shown minor or significant disagreements between fire behaviour observations and predictions which have often been attributed to the inadequacy of stylized fuel models to represent the existing forest fuel conditions.

In Greece, some testing of BehavePlus took place after the fires of 2007 which had mostly spread under extreme weather conditions and had caused huge damages (Athanasiou and Xanthopoulos, 2010). That testing had shown a very good agreement between fire behaviour observations and predictions for tall Mediterranean shrublands that were described by the "Evergreen-schlerophyllous shrublands (1.5 - 3 m)" fuel model for tall maquis, which had been developed and published earlier (Dimitrakopoulos *et al* 2001, Dimitrakopoulos 2002). The collection of fire behaviour data continued in the field during the following fire seasons, enriching the database and allowing a "stress test" of the initial and preliminary conclusions for the above model, in a wider range of conditions.

Moreover, additional fire behaviour data were recorded presenting an opportunity for testing BehavePlus surface fire behaviour predictions for three more fuel types: a) short maquis, b) small xeric shrubs, up to 0.5 m height (called phrygana in Greece) and c) grass. These types can be described by three previously developed fuel models for Greece by the same authors: a) "Evergreen schlerophyllous shrublands (up to 1.5 m)", b) "Phrygana II (*Sarcopoterium spinosum*)" and c) "Mediterranean grasslands".

The current paper is part of the Ph.D. thesis of the first author. A data subset of documented wildfires of the last seven fire seasons (2007 – 2013) in Greece were utilised, aiming to evaluate the degree of agreement of BehavePlus predictions with observed fire behaviour for four out of the seven fuel models that have been developed for Greece, to introduce adjustments if needed, and ultimately to contribute towards wider adoption of prediction systems into fire management.

## 2. Methods

A database including meteorological, topography, forest fuels and fire behaviour data was initially created in 2007 and is continuously enlarged with field measured observations made during specific fires. It now consists of detailed data collected during 32 low, medium or high intensity wildfires which took place under a variety of meteorological conditions, topography and fuels. More than one data records (fire behaviour cases) resulted from each of these fires as most of them run their course for many hours. The database now includes 185 records. Its fields contain detailed information about the observed fire rate of spread and flame length and reliable data about the fire type, crowning initiation and propagation, crown fire type, spreading in canyon, spotting (Athanasiou and Xanthopoulos, 2013), wind direction versus slope, wind adjustment factor and midflame wind speed (Rothermel, 1983), downslope or upslope fire spread, fire spread direction in relation to wind (head fire, backward, or sideward moving) and, where relevant, such observations as strong wind turbulence occurrence, convection column generation, etc.

### 2.1. Fieldwork and data processing

The fire behaviour observations were matched with the related meteorological, topography and forest fuels information following specific procedures (Athanasiou and Xanthopoulos, 2010). The forest fuel types, in which the fires spread, were identified through visual assessment and were described by the suitable fuel models for Greece when such a description was possible. Slope, aspect and altitude were measured using a Garmin etrex Summit GPS device in the field, and later using the ArcGIS 9.3 Geographic Information System (GIS) software by ESRI Corporation in the office. Air temperature in degrees Celsius ($^oC$), relative humidity in (%) and wind speed and gusts in kilometers per hour (km/h), were measured using an electronic weather instrument (type: Thermometer – Anemometer - Hygrometer Model N$^o$ AM4205). Additionally, wind direction azimuth was determined using a compass.

Fire rate of spread ($ROS_{observed}$), in (km/h), was calculated by knowing the exact time for every fire head, finger, tail or flank location (Alexander and Thomas, 2003) and applying simple geometry (Clements *et al*., 1983) or using the GIS software, through the following steps:

a) recording the geographic coordinates of observer's positions with the GPS device and measuring the observations' horizontal azimuth with a compass,
b) taking plenty of sequential digital photographs (in JPG format and known time) using a Canon Powershot S3is digital camera [which has a lens with a focal length ranging from 36 mm (wide Angle) to 432 mm (telephoto)],
c) pinpointing the sequential locations of the fire on the photograph (figures 1, 2, 3 and 4) or on the map.

Flame length ($FL_{observed}$) in (m), was calculated also by applying simple geometry (Clements *et al*., 1983) for the cases that this was possible.

### 2.2. Defining the fire behavior data samples

The first step of the analysis was the preparation of the data according to specific criteria in order to ensure data quality and compatibility. Active crown fires and cases of surface fire behaviour affected by spotting, a strong convection column or other factors that resulted in extreme fire behaviour (e.g. box canyon or turbulence) were excluded. The excluded cases fall in two main categories of: a) fires that were dominated by factors that cannot be explained by the ordinary fire spread physical laws, therefore these cases are not comparable with BehavePlus predictions or b) fires which spread in fuel situations and complexes that consist of several mixed fuel types that cannot yet be described by the existing seven fuel models, for Greece. The remaining 95 cases of surface or passive crown fire behaviour ($ROS_{observed(surface)}$) were then classified depending on the fuel model that describes the fuel types they had spread in. Four data subsets were generated that correspond to the following four fuel models for Greece:

a) "Evergreen-schlerophyllous shrublands (1.5 - 3 m)" for tall maquis (38 cases),
b) "Evergreen schlerophyllous shrublands (up to 1.5 m)" for short maquis (13 cases),
c) "Phrygana II (*Sarcopoterium spinosum*)" for phryganic areas where the dominant species was *Sarcopoterium spinosum* (26 cases) and
d) "Mediterranean grasslands" for grass (18 cases).

***1(a): Photo captured at 18:22:36***

***1(b): Photo captured at 18:57:38***

***Figure 1(a) & (b) - Fire spread of 55 meters in tall maquis (yellow arrow), downslope, within a period of 35 minutes and 2 seconds. $ROS_{observed}$ = 0.09 km/h***

*2(a): Photo captured at 14:34:36* *2(b): Photo captured at 14:35:36*

***Figure 2(a) & (b) - Fire spread of 12.5 meters in low maquis (yellow arrow), upslope, within a period of 1 minute. $ROS_{observed}$ = 0.75 km/h***


***Figure 3. Fire spread of 80 meters in phrygana (yellow arrow), downslope, within a period 3 minutes and 54 seconds. $ROS_{observed}$ =1.23 km/h***

*4(a): Photo captured at 15:44:00*

*4(b): Photo captured at 15:44:15*

***Figure 4(a) & (b) - Fire spread of 36 meters in grass (yellow arrow), on flat terrain, within a period of 15 seconds. $ROS_{observed}$ = 8.64 km/h***

## 3. Analysis

On-site meteorological measurements, measured slope values and the four fuel models for tall maquis, short maquis, *Sarcopoterium spinosum* dominated phryganic areas and grass, were used as inputs for predicting surface fire rate of spread values ($ROS_{predicted\ (surface)}$) with BehavePlus. The values of the four fuel models parameters are summarized and reported in table 1 and typical photos are shown in Figure 5 in an effort to facilitate further testing by researchers and use by fire managers in Mediterranean countries with fuel situations that can be described by these fuel models.

The NEWMDL module of the original BEHAVE system (Burgan and Rotrhermel 1984) was used to calculate the overall fuel load in the dead fine fuels (1hr) category of the fuel models, adding the load of litter to that of the rest of 1 hr fuels and then to calculate a weighted fuel bed depth. Furthermore, NEWMDL produced an estimate for the "dead fuel moisture of extinction" for each model. Such values had not been reported previously.

Fine (1-h) dead Fuel Moisture Content (FMC %) value was calculated using Rothermel's methodology (1983) using: a) air temperature and relative humidity measurements, b) month and time of day of the observation, c) elevation difference between the location where the meteorological measurements were made and the fire spread location, d) slope and aspect of the fire spread location and e) surface fuels shading percentage.

***Table 1. The values of the parameters of the four fuel models that were used as inputs for predicting surface fire rate of spread ($ROS_{predicted(surface)}$) with BehavePlus.***

| FUEL MODEL / PARAMETER | Evergreen schlerophyllous shrublands (1.5 – 3.0 m) | Evergreen schlerophyllous shrublands (up to 1.5 m) | Phrygana II (*Sarcopoterium spinosum*) | Mediterranean grasslands |
|---|---|---|---|---|
| **1 HR (MTON/HA)** | 17.88 | 9.91 | 3.50 | 4.82 |
| **10 HR (MTON/HA)** | 13.30 | 6.80 | 1.02 | 0.49 |
| **100 HR (MTON/HA)** | 8.5 | 3.60 | 0.28 | 0 |
| **LIVE HERB (MTON/HA)** | 0 | 0 | 0 | 0 |
| **LIVE WOODY (MTON/HA)** | 10.60 | 7.70 | 0.85 | 0 |
| **1 HR S/V (1/CM)** | 55 | 55 | 65 | 78 |

| | | | | |
|---|---|---|---|---|
| **LIVE HERB S/V (1/CM)** | - | - | - | - |
| **LIVE WOODY S/V (1/CM)** | 55 | 55 | 65 | - |
| **FUEL BED DEPTH (CM)** | 203.58 | 102.19 | 40.00 | 27.53 |
| **EXT MOISTURE (%)** | 34 | 34 | 20 | 14 |
| **HEAT CONTENT (J/G)** | 20000 | 20000 | 19054 | 18600 |

The 10-h dead FMC value was assumed equal to the 1-h dead FMC also (Andrews *et al.*, 2005) (which is a commonly applied and acceptable approach) while the necessary 100-h dead FMC% and live woody FMC% values were assigned according to values of unpublished measurements in Attica for that time period and year.

***Figure 5(a). Tall maquis fuel model***

***Figure 5(b). Short maquis fuel model***

***Figure 5(c). Phrygana II fuel model***

***Figure 5(d). Grass fuel model***

The 26 surface fire behaviour observations in phryganic areas included 26 $FL_{observed}$ values that consist a complete subset which could be compared with predictions ($FL_{predicted}$ values) that were obtained using the fuel model "Phrygana II (*Sarcopoterium spinosum*)".

## 4. Results

The maximum, minimum, mean and standard deviation of $ROS_{observed(surface)}$ values for the subsets of 38, 13, 26 and 18 observations, referring to surface fire behaviour during pure surface fires or passive crown fires, are reported in table 2.

***Table 2. Descriptive statistics summary of surface $ROS_{observed(surface)}$ values for the four fuel types (N:number of observations / cases)***

| ROS values (km/h) | **Tall maquis N = 38** | **Short maquis N = 13** | **Phrygana II (dominant species: *Sarcopoterium spinosum*) N = 26** | **Grass N = 18** |
|---|---|---|---|---|
| *max* | 3.31 | 1.65 | 2.71 | 11.03 |
| *min* | 0.09 | 0.05 | 0.02 | 0.04 |
| *mean* | 0.90 | 0.45 | 0.54 | 1.95 |
| *std. deviation* | 0.80 | 0.45 | 0.59 | 3.28 |

The pairs of rate of spread observed values ($ROS_{observed(surface)}$) and BehavePlus predicted values ($ROS_{predicted(surface)}$), were correlated via linear regression, for every fuel model subset, resulting in the four following equations. The plots of these equations are shown in figure 6.

$\mathbf{ROS_{observed} = 0.165 + 0.886 * ROS_{predicted}}$, adjusted $\mathbf{R^2 = 0.806}$, (tall maquis) (1)

$\mathbf{ROS_{observed} = 0.127 + 0.709 * ROS_{predicted}}$, adjusted $\mathbf{R^2 = 0.873}$, (short maquis) (2)

$\mathbf{ROS_{observed} = 0.101 + 0.783 * ROS_{predicted}}$, adjusted $\mathbf{R^2 = 0.681}$, (*Sarcopoterium spinosum*) (3)

$\mathbf{ROS_{observed} = -0.023 + 1.562 * ROS_{predicted}}$, adjusted $\mathbf{R^2 = 0.847}$, (grass) (4)

The four equations are statistically significant ($p<0.001$) and the p-values of their slope coefficients are statistically significant ($p<0.001$). The p-values of the constants of equations (1), (3) and (4) are not statistically significant ($p\text{-value}_1=0.052$, $p\text{-value}_3=0.266$ and $p\text{-value}_4=0.950$, respectively) while the p-value of the constant of equation (2) is statistically significant ($p\text{-value}_2=0.046$).
The adjusted $R^2$ values of the regression equations (1), (2) and (4) indicate that their unexplained errors are low while the adjusted $R^2$ value of equation (3) shows that the unexplained error is relatively higher. This is probably the result of using this fuel model to describe fuel situations and complexes of significant heterogeneity (figure 6c).
The ROS data subsets analysis was followed by a preliminary investigation that concerned the FL of surface fires in phryganic areas (figure 7). Plotting the observed and predicted FL values for the 26 cases in this subset it became clear that in only two cases $FL_{observed}$ was lower than $FL_{predicted}$. The ratio between $FL_{observed}$ and $FL_{predicted}$ varied between 0.3 and 5.0 with an average value of 2.3 and a standard deviation of 1.2. In general, $FL_{observed}$ values were more than twice the values of $FL_{predicted}$ for the fuel model Phrygana II.

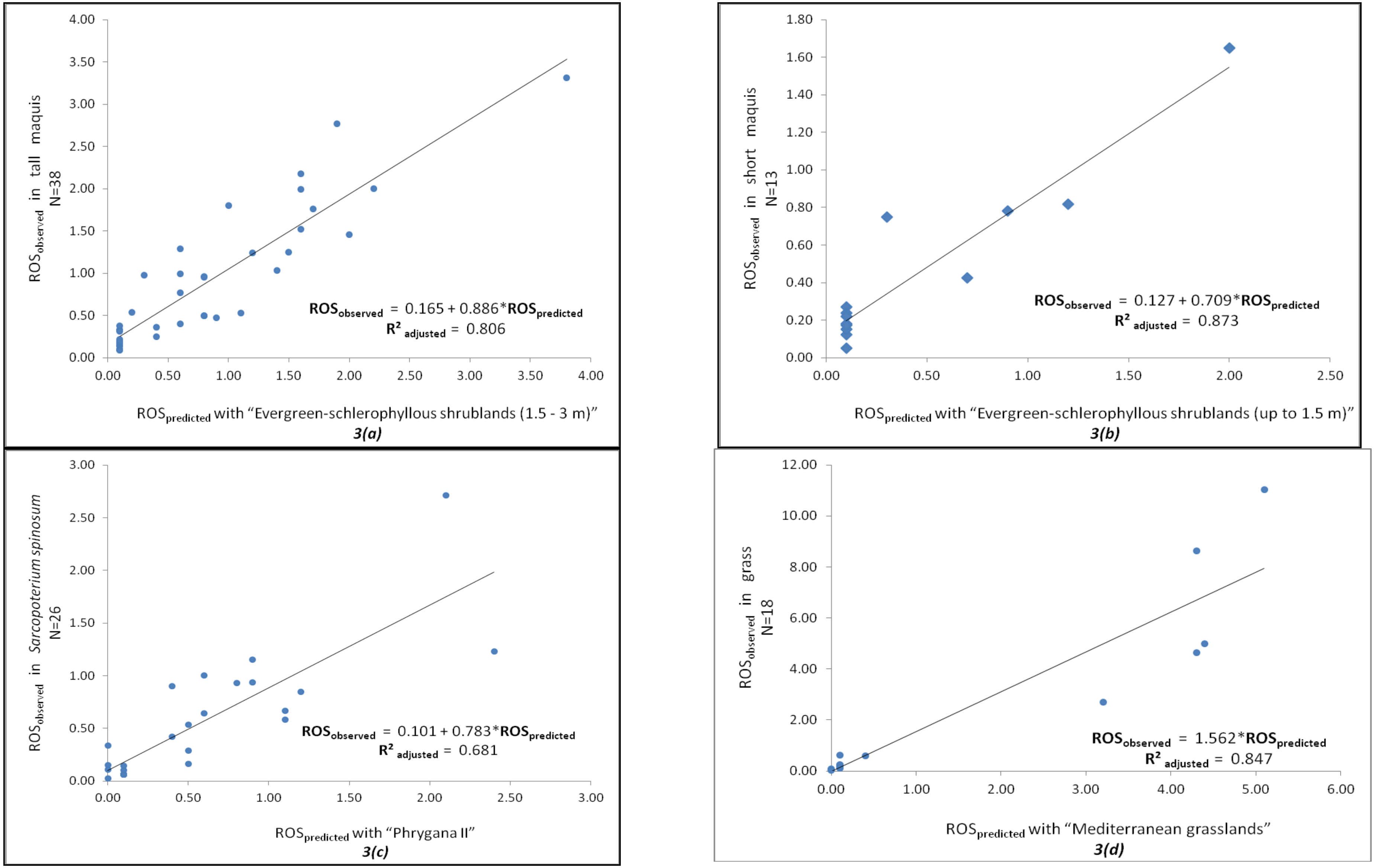


***Figure 6 (a), (b), (c) & (d): – Correlations of surface $ROS_{observed}$ and $ROS_{predicted}$ values (in km/h) for the four data subsets***

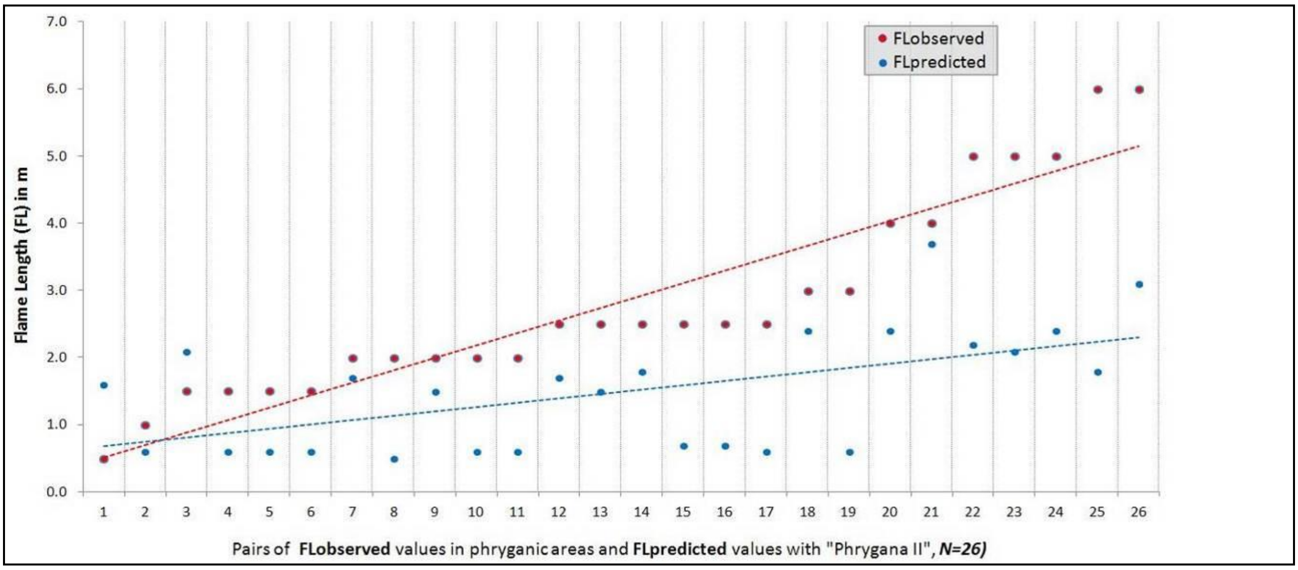


***Figure 7. Plot of observed and predicted flame length for Sarcopoterium spinosum dominated phrygana fields. The pairs of values are sorted in ascending order of $FL_{observed}$.***

## 5. Discussion

The pairs of $ROS_{observed(surface)}$ values and BehavePlus $ROS_{predicted(surface)}$ values, were correlated via linear regression for each of the data subsets, resulting in four statistically significant ($p<0.001$) equations with good adjusted $R^2$ values. The p-values of their slope coefficients were also statistically significant ($p<0.001$). This was not true for the constants of the equations for tall maquis, *Sarcopoterium spinosum* and grass, whereas the constant of the equation for short maquis was statistically significant. The non-significance of the constants of the three equations means that this term is not significantly different from 0.

The unexplained error of the equations was low for the short and tall maquis as well as for grass but was higher for the quite flammable xeric shrub *Sarcopoterium spinosum*. This higher unexplained error may be attributed to the fact that the fuel model "Phrygana II (*Sarcopoterium spinosum*)" was used to describe relatively heterogeneous fuel situations, including for example a variable percentage of other phryganic species such as *Cistus creticus*, *Cistus salvifolius*, etc.

Table 3 shows the calculated $ROS_{observed(surface)}$ values from solving the four equations for a range of plausible $ROS_{predicted(surface)}$ values, providing an insight on the degree of agreement of predictions vs observations for the level of accuracy that is required in operational applications. From this table it becomes clear that the agreement for the fuel model "Evergreen-schlerophyllous shrublands (1.5 - 3 m)" is very good, confirming the conclusions of Athanasiou and Xanthopoulos (2010). Due to this good agreement it seems unnecessary to adjust BehavePlus ROS predictions to the somewhat lower "real world" values that would result from corrections based on equation (1).

The agreement for the "Evergreen schlerophyllous shrublands (up to 1.5 m)" and for the "Phrygana II" models is also relatively good although it is clear that BehavePlus predictions are quite higher than the ROS observations. Because of this over-prediction it is advisable, when obtaining ROS estimates for fires in these two fuel models, to adjust these estimates using equations (2) and (3) respectively. It should be mentioned here that equation (2), in spite of its good adjusted $R^2$ value and the fact that its constant and slope coefficient are statistically significant, should be considered as preliminary. The number of observations that were analysed was small (N=13) so the result does not inspire confidence for broad operational use. Further work is needed for this fuel type.

***Table 3. Solution of equations (1)-(4) for a range of values of $ROS_{predicted(surface)}$ (km/h).***

| | ROSobserved(surface) | | | |
|---|---|---|---|---|
| ROSpredicted(surface) | Tall maquis | Short maquis | Phygana II | Grass |
| 0 | 0.165 | 0.127 | 0.101 | -0.023 |
| 1 | 1.051 | 0.836 | 0.884 | 1.539 |
| 2 | 1.937 | 1.545 | 1.667 | 3.101 |
| 3 | 2.823 | 2.254 | 2.450 | 4.663 |
| 4 | 3.709 | 2.963 | 3.233 | 6.225 |
| 5 | 4.595 | 3.672 | 4.016 | 7.787 |
| 6 | 5.481 | 4.381 | 4.799 | 9.349 |
| 7 | 6.367 | 5.09 | 5.582 | 10.911 |
| 8 | 7.253 | 5.799 | 6.365 | 12.473 |
| 9 | 8.139 | 6.508 | 7.148 | 14.035 |
| 10 | 9.025 | 7.217 | 7.931 | 15.597 |

In the case of grasslands, table 3 shows that BehavePlus strongly underpredicts ROS. As equation (4) is statistically significant and its adjusted $R^2$ value is high ($R^2_{adjusted}$ = 0.847), this under-prediction should be taken into consideration when using BehavePlus for ROS prediction in grasslands with the Greek grass fuel model. Equation (4) should be used for obtaining adjusted $ROS_{observed(surface}$ i.e. "real world" ROS estimates.

The analysis of flame length in phryganic areas showed that on average $FL_{observed}$ was 2.3 times greater than the $FL_{predicted}$ values obtained through BehavePlus using the Phrygana II fuel model. The FL predictions tended to underestimate notably the actual FL that was measured in the field. There were only two exceptions, out of the twenty six cases, in which $FL_{predicted}$ was greater than the $FL_{observed}$ value (figure 7).

Underestimating the expected FL in phrygana is a serious problem for another reason as well: as shown in figure 7 the underestimation takes place in a narrow band of FL values that includes the FL threshold value of 1.2 m which is considered as the limit for direct attack on the flames with hand tools (Deeming *et al*., 1977, Hirsch and Martell, 1996). For ten out of the twenty six cases the prediction value was lower than the hand tools threshold value while the actually observed flame length was greater than that.

Phrygana have been the cause of many firefighting accidents in Greece as they are flashy fuels and respond very quickly to changes of the environmental conditions (wind, topography, relative humidity) (Xanthopoulos, 2007). The reliability of FL predictions for a wide range of meteorological conditions, topography and fuel situations is crucial and mandatory since flame length affects the personnel extinguishment capacity and FL predictions inaccuracy could jeopardize the safety of the firefighters in these fine, quite flammable and flashy fuels.

## 6. Conclusions

The main finding of the work presented here is that for the four Greek fuel models tested, BehavePlus can be a useful tool for predictions of fire behaviour. However, there is a relatively consistent over-prediction of ROS for the models "Evergreen-schlerophyllous shrublands (1.5 - 3 m)" for tall maquis, "Evergreen schlerophyllous shrublands (up to 1.5 m)" for short maquis (13 cases), and "Phrygana II (*Sarcopoterium spinosum*)", while there is a significant under-prediction for the "Mediterranean grasslands" fuel model.

The four linear regression equations that were developed are statistically significant and can be used for adjusting BehavePlus predictions to match "real world" fire behaviour, at least as documented in

the present study. Such an adjustment could also be incorporated in fire spread simulation systems used in Greece.
The finding that flame length is seriously under-predicted when using BehavePlus with the Phrygana II fuel model to predict fire behaviour in Sarcopoterium spinosum dominated phrygana fields is an important result that can be very useful for the safety of firefighters. It should be seriously taken into consideration in operational firefighting in the country.
Future work, as data continue being collected and the data base is expanded, are expected to shed additional light in the issues discussed in this paper, ultimately improving fire behaviour prediction and firefighter safety in Greece.

## 7. Aknowledgements

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